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RESEARCH MEMORANDUM

TWO-DIMENSIONAL WIND-TUNNEL INVESTIGATION OF

A 6-PERCENT-THICK SYMMETRICAL CIRCULAR-ARC AIRFOIL

SECTION WITH LEADING-EDGE AND TRAILING-EDGE

HIGH-LIFT DEVICES DEFLECTED IN COMBINATION

By Robert J. Nuber and Gail A. Cheesman

Langley Aeronautical Laboratory
Langley Air Force Base, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

A two-dimensional wind-tunnel investigation was made of a
6-percent-thick symmetrical circular-arc airfoil with leading-edge
and trailing-edge high-lift devices. The investigation was made to
determine the effects on maximum section lift coefficient of different
leading-edge slats and drooped-nose flaps of 15-percent chord when used
in combination with a plain trailing-edge flap of 20-percent chord
deflected 60°. Section lift characteristics of the airfoil with the
various high-lift devices deflected in combination are presented for
Reynolds numbers from 0.7×10^6 to 9.0×10^6. Slat-position contours
of maximum section lift coefficient and some pitching-moment charac-
teristics are included.

The results indicated that a properly positioned leading-edge slat
or a drooped-nose flap increased the maximum section lift coefficient
of the airfoil with the plain trailing-edge flap deflected 60°
from 1.63 to 2.02 or 1.96, respectively, and increased the angle of
attack for maximum section lift coefficient from 2.5° to 16° or 9°,
respectively. It was also found that varying the Reynolds number for
either the slat or drooped-nose-flap configurations or moving the
drooped-nose-flap hinge from the lower surface to the upper surface
had essentially no effect on the lift characteristics.

INTRODUCTION

The use of wings with thin biconvex profiles for high-speed air-
craft has necessitated the development of devices to increase the low

maximum lift coefficients of these profiles in order that the airplane
may fly satisfactorily in the low-speed range. Devices that have been
suggested for this purpose are trailing-edge flaps, leading-edge flaps,
and leading-edge slats. Of these devices, trailing-edge flaps and
leading-edge flaps have been investigated. (See reference 1.)

The present paper gives the results of an investigation of a
6-percent-thick symmetrical circular-arc airfoil with a 15-percent-
chord leading-edge slat deflected in combination with a 20-percent-
chord plain trailing-edge flap having a 60° deflection. These results
include the section lift characteristics, slat-position contours of
maximum section lift coefficient, and some pitching-moment charac-
teristics. Also included in the investigation are the effects on the
section lift characteristics of varying the Reynolds number and of
moving the hinge line from the lower surface to the upper surface of
a 15-percent-chord leading-edge flap deflected 27° in combination with
the 20-percent-chord plain trailing-edge flap having a deflection
of 60°.

SYMBOLS

c_l section lift coefficient $\left(\dfrac{l}{q_0 c}\right)$

$c_{m_{c/4}}$ section pitching-moment coefficient about the quarter chord

           $\left(\dfrac{m_{c/4}}{q_0 c^2}\right)$

where

l lift per unit span

m pitching moment per unit span

c chord of airfoil with high-lift devices neutral

q_0 free-stream dynamic pressure $\left(\dfrac{\rho_0 V_0^2}{2}\right)$

ρ_0 free-stream mass density

V_0 free-stream velocity

α_0 section angle of attack, degrees

$c_{l_{max}}$ maximum section lift coefficient

$\Delta c_{l_{max}}$ increment of maximum section lift coefficient due to
                  deflection of leading-edge high-lift devices

$\alpha_{c_{l_{max}}}$ section angle of attack at maximum lift coefficient

$\Delta\alpha_{c_{l_{max}}}$ increment of section angle of attack at maximum lift due to
                  deflection of leading-edge high-lift devices

R Reynolds number

δ_s angular deflection of leading-edge-slat chord line from
                  airfoil chord line, positive when deflected below chord
                  line, degrees

δ_N drooped-nose-flap deflection, positive when deflected below
                  chord line, degrees

δ_F plain trailing-edge-flap deflection, positive when deflected
                  below chord line, degrees

x_s horizontal distance from reference point on main part of
                  airfoil to the slat trailing edge, positive when slat
                  moves forward, percent of airfoil chord

y_s vertical distance from reference point on main part of
                  airfoil to slat trailing edge, positive when slat moves
                  upward, percent of airfoil chord

MODEL

The model used in this investigation was a 24-inch-chord airfoil
section built to a 6-percent-thick symmetrical circular-arc contour.
Ordinates for this profile are presented in table I. The main part of
the airfoil was made of steel. The 20-percent-chord plain trailing-
edge flap, constructed of brass, was pivoted on leaf hinges mounted
flush with the lower surface. (See reference 1.) The gap between the
flap and flap skirt was sealed with modeling clay to prevent leakage.
In all cases, the leading-edge slats and drooped-nose flaps were
investigated in combination with the plain trailing-edge flap
deflected 60°.

Slats.-- The slats were constructed of brass and had chords equal
to 15 percent of the airfoil chord. Ordinates and sketches of the
three slat configurations tested are given in table II and figure 1,
respectively.

Configurations 1 and 2 were designed so that, when the slats were
retracted, they faired into the main part of the airfoil. For configu-
ration 3, a small gap between the slat and main part of the airfoil
existed on the lower surface with the slat neutral. Model end plates,
as shown in figure 2, were used to facilitate changing the slat to any
desired position. Slat end plates, which recessed into the model end
plates, were used to change the slat deflection. The slat trailing-
edge positions were measured from a reference point located on the
upper surface of the main part of the airfoil at the 15-percent-chord
station, as shown in figure 3. No intermediate supports were provided
between the main part of the airfoil and the slat.

Drooped-nose flap.-- The drooped-nose flaps were constructed of
brass and had chords equal to 15 percent of the airfoil chord. For all
tests, these flaps were deflected 27°. Configuration A was designed
so that the drooped-nose flap pivoted on a leaf hinge-mounted flush
with the lower surface, and the flap skirt was in rubbing contact with
the flap. A sketch of this configuration is shown in figure 1. In
order to determine the aerodynamic effects of changing the position of
the hinge line, a lead bead was soldered to the upper surface of the
flap and filed to a sharp corner. A sketch of this modification,
designated configuration B, is also shown in figure 1.

TESTS

The investigation was conducted in the Langley two-dimensional
low-turbulence tunnel and the Langley two-dimensional low-turbulence
pressure tunnel. A complete description of these wind tunnels, details
of the test methods, and the methods used in correcting the data to
free-air conditions are given in reference 2. All tests were made with
the 20-percent-chord plain trailing-edge flap deflected 60° in
combination with the leading-edge high-lift devices.

Slat.-- Measurements were made at a Reynolds number of 2.0×10^6 of
the lift of the slat configurations to determine the ideal positions
of the slats. The ideal position of the slat for a given deflection
and slat configuration is defined as the position that yields the
highest maximum section lift coefficient. For these tests, a wide
horizontal and vertical range of slat locations was covered for several
slat deflections and three slat configurations.

Section lift characteristics were determined for configuration 1 at a Reynolds number of 2.0×10^6 for slat deflections of 19.75°, 25.5°, 30°, and 35.25°. Pitching moments were measured only for slat configuration 1 with the slat deflected 25.5° and 30°. The section lift characteristics of slat configuration 2 were determined at Reynolds numbers of 2.0×10^6, 6.0×10^6, and 9.0×10^6 with the slat deflected 30° and for configuration 3 at a Reynolds number of 2.0×10^6 with the slat deflected 30°. Additional lift data for configurations 2 and 3 with the slats deflected 35° were obtained but are not included in this paper because the range of horizontal and vertical slat locations covered was insufficient to form a set of contours. These data, however, were found to be less favorable than those obtained with the slats deflected 30°.

Drooped-nose flap.- The lift characteristics were determined for drooped-nose-flap configuration A (hinge line on lower surface of drooped-nose flap) through a range of Reynolds numbers from 0.70×10^6 to 2.29×10^6. The lift characteristics of configuration B (hinge line on upper surface of drooped-nose flap) were determined at Reynolds numbers of 2.0×10^6 and 6.0×10^6.

RESULTS AND DISCUSSION

Slat configurations.- Contours of maximum section lift coefficient obtained at a Reynolds number of 2.0×10^6 are presented in figures 4, 5, and 6 for the three slat configurations at various slat positions and deflections. Maximum section lift coefficients and angles of attack for maximum lift coefficient at the ideal slat positions for given slat deflections are shown in these figures. The contours illustrate the sensitivity of the maximum section lift coefficient to changes in slat location for given slat deflections. Variation in slat trailing-edge height from the ideal position, particularly for an upward displacement, appears to be more critical, on the average, than chordwise variation.

The highest maximum section lift coefficients for each of the three slat configurations investigated occurred at a slat deflection of 30°.

The lift characteristics obtained at a Reynolds number of 2.0×10^6 for slat configurations 1, 2, and 3 with the slats deflected 30° and located at their ideal positions are presented in figure 7. The magnitude of the maximum section lift coefficients varied from a value of 1.94 for configuration 2 to a value of 2.02 for configuration 3. It should be noted, however, that a small gap between the slat and the

airfoil exists on the lower surface of configuration 3 with the slat retracted. If such profile irregularities are to be avoided, particularly for supersonic flight, then configuration 1, which produces a maximum lift coefficient of 2.00, may be considered the most effective.

The section lift and pitching-moment characteristics of configuration 1, obtained at a Reynolds number of 2.0×10^6 for the ideal positions of the slat for several slat deflections, are presented in figure 8. The maximum section lift coefficient for the 25.5° slat deflection is nearly equal to that obtained with a deflection of 30°. The aerodynamic center remains ahead of the quarter-chord point as shown by the section pitching-moment characteristics. For the 30° slat deflection, figure 8 shows that the magnitude and manner of variation of the moment coefficients are generally the same as those obtained with the drooped-nose flap deflected 30°.

The section lift characteristics of configuration 2, obtained at Reynolds numbers from 2.0×10^6 to 9.0×10^6 with the slat deflected 30°, are presented in figure 9. The maximum section lift coefficients are relatively unaffected by increases in the Reynolds number. Since no appreciable scale effect was obtained with configuration 2, it is believed that the effects of Reynolds number variations on $c_{l_{max}}$ for configurations 1 and 3 also may be considered negligible.

Drooped-nose-flap configurations.— The section lift characteristics of configuration A are presented in figure 10 for Reynolds numbers from 0.70×10^6 to 2.29×10^6. It is seen in figure 10 that the maximum section lift characteristics remain practically constant with increasing Reynolds number. These results conform, in this respect, with the data presented in references 1 and 3 for the 6— and 7.5—percent-thick circular-arc airfoils with corresponding flap deflections.

The section lift characteristics of configuration B are presented in figure 11 for Reynolds numbers of 2.0×10^6 and 6.0×10^6. Included in the figure for comparison are the section lift characteristics of configuration A corresponding to a Reynolds number of 2.0×10^6. The lift characteristics were practically unaffected when the hinge line of the drooped-nose flap was moved from the lower surface to the upper surface or when the Reynolds number of configuration B was increased from 2.0×10^6 to 6.0×10^6.

It may be noted that the lift curves for configuration A at a Reynolds number of 1.98×10^6 (fig. 10) and at a Reynolds number of 2.0×10^6 (fig. 11) are not quite in agreement near maximum lift.

The discrepancies are not considered important and may be attributed to the fact that the two runs were made in different tunnels with a time interval of about 2 years between tests.

The maximum section lift coefficient of the airfoil with the plain trailing-edge flap deflected 60° (reference 1) is increased from a value of 1.63 to 1.96, and the angle of attack for maximum section lift coefficient is increased from 2.5° to 9° when the drooped nose is deflected 27° (configuration B).

Comparison of slat and drooped-nose-flap configurations.— Increments of maximum section lift coefficient $\Delta c_{l_{max}}$ and increments of section angle of attack for maximum lift coefficient $\Delta \alpha_{c_{l_{max}}}$ that result from deflection of the slat or drooped-nose flap are summarized graphically in figure 12. Included in the figure are comparative data taken from reference 1 ($R = 6.0 \times 10^6$) for several deflections of the drooped-nose flap. The increments in maximum section lift coefficient for slat configuration 1 over a large range of deflections are greater than those obtained with the drooped-nose flap. Increments in angle of attack for maximum section lift coefficient are greater for the slats than for the drooped-nose flaps but the lift-curve peaks are similar. The differences in maximum section lift coefficient can be attributed, in part, to the greater projected area of the slat configurations. It must be emphasized, however, that, although slat configurations 1 and 3 are slightly more effective than the other leading-edge high-lift devices investigated, the drooped-nose-flap configurations may be more attractive to the designer in view of the structural and mechanical problems presented by slatted airfoils and because of the sensitivity of the maximum section lift coefficients of slatted airfoils to slat-position changes resulting from air loads and manufacturing irregularities.

It is believed that the air loads on the slats may be substantially equivalent to the air loads on the drooped-nose flap (reference 4) for corresponding deflections because the peak pressures near the leading edge of both types of high-lift devices are limited by separation.

Table III presents a summary of the highest maximum section lift coefficients, the angles of attack at which the maximum section lift coefficients occurred, and the increments that were obtained for the slat and drooped-nose-flap configurations investigated at a Reynolds number of 2.0×10^6. Also included in table III are the maximum section lift coefficients and angles of attack for maximum lift coefficient obtained at a Reynolds number of 6.0×10^6 for the plain airfoil and the airfoil with the plain trailing-edge flap deflected 60° (reference 1).

CONCLUSIONS

The results of a two-dimensional wind-tunnel investigation at Reynolds numbers from 0.70×10^6 to 9.0×10^6 of a 6-percent-thick symmetrical circular-arc airfoil with either a 15-percent-chord leading-edge slat or a 15-percent-chord drooped-nose flap and a 20-percent-chord plain trailing-edge flap deflected 60° indicated the following conclusions:

1. A properly positioned leading-edge slat or a drooped-nose flap increased the maximum section lift coefficient of the airfoil with the plain trailing-edge flap deflected 60° from a value of 1.63 to 2.02 or 1.96, respectively, and increased the angle of attack for maximum section lift coefficient from 2.5° to 16° or 9°, respectively.

2. The maximum section lift characteristics of the slat configurations are extremely sensitive to changes from the ideal slat position.

3. The type of lift-curve peak and the magnitude and manner of variation of the pitching-moment coefficients of the slat and drooped-nose-flap configurations are similar for a deflection of 30°.

4. The maximum section lift characteristics of the slat and drooped-nose-flap configurations tested are relatively unaffected by variations of Reynolds number.

5. Moving the position of the drooped-nose-flap hinge from the lower surface to the upper surface had practically no effect on the lift characteristics.

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                Langley Air Force Base, Va.

REFERENCES

1. Underwood, William J., and Nuber, Robert J.: Two-Dimensional Wind-Tunnel Investigation at High Reynolds Numbers of Two Symmetrical Circular-Arc Airfoil Sections with High-Lift Devices. NACA RM L6K22, 1947.

2. Von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.

3. Powter, G. J., and Young, A. D.: Wind Tunnel Tests on a 7.5-Percent-Thick Bi-Convex Wing with Leading and Trailing Edge Flaps. R.A.E. Rep. No. Aero. 2157, British R.A.E., Sept. 1946.

4. Underwood, William J., and Nuber, Robert J.: Aerodynamic Load Measurements over Leading-Edge and Trailing-Edge Plain Flaps on a 6-Percent-Thick Symmetrical Circular-Arc Airfoil Section. NACA RM L7H04, 1947.

TABLE I

ORDINATES FOR THE PLAIN AIRFOIL

[Stations and ordinates given
in percent of airfoil chord]
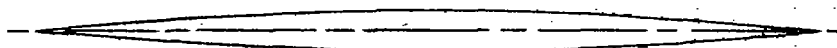
6-percent-thick symmetrical circular-arc airfoil			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
5	.572	5	-.572
10	1.082	10	-1.082
15	1.533	15	-1.533
20	1.922	20	-1.922
25	2.252	25	-2.252
30	2.521	30	-2.521
35	2.731	35	-2.731
40	2.880	40	-2.880
45	2.970	45	-2.970
50	3.000	50	-3.000
55	2.970	55	-2.970
60	2.880	60	-2.880
65	2.731	65	-2.731
70	2.521	70	-2.521
75	2.252	75	-2.252
80	1.922	80	-1.922
85	1.533	85	-1.533
90	1.082	90	-1.082
95	.572	95	-.572
100	0	100	0

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TABLE II

LEADING-EDGE SLAT AND MAIN AIRFOIL NOSE ORDINATES

[Station and ordinates given in percent of airfoil chord]

LEADING-EDGE SLAT

CONFIGURATION 1			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.500	.060	.500	-.060
.750	.090	.750	-.090
1.250	.149	1.250	-.149
2.500	.293	2.500	-.293
5.000	.572	5.000	-.572
7.500	.835	7.500	-.835
10.000	1.082	10.000	-1.082
15.000	1.533	10.458	-1.133
		10.667	-.492
		10.833	-.204
		11.250	.254
		12.083	.821
		12.917	1.150
		13.750	1.350
		15.000	1.533

CONFIGURATION 2			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.500	.060	.500	-.060
.750	.090	.750	-.090
1.250	.149	1.250	-.149
2.500	.293	2.500	-.293
5.000	.572	5.000	-.572
7.500	.835	7.500	-.835
10.000	1.082	10.000	-1.082
15.000	1.533	11.875	-1.258
		11.417	-1.163
		11.083	-.933
		10.504	-.667
		10.667	-.492
		10.833	-.204
		11.250	.254
		12.083	.821
		12.917	1.150
		13.750	1.350
		15.000	1.533

CONFIGURATION 3			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.500	.060	.500	-.060
.750	.090	.750	-.090
1.250	.149	1.250	-.149
2.500	.293	2.500	-.293
5.000	.572	5.000	-.572
7.500	.835	7.500	-.835
10.000	1.082	10.000	-1.082
15.000	1.533	10.250	-1.042
		10.417	-.929
		10.583	-.650
		10.667	-.492
		10.833	-.204
		11.250	.254
		12.083	.821
		12.917	1.150
		13.750	1.350
		15.000	1.533

TABLE II — Concluded

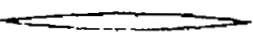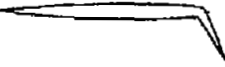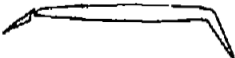LEADING-EDGE SLAT AND MAIN AIRFOIL NOSE ORDINATES — Concluded
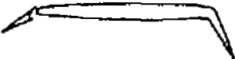
MAIN AIRFOIL NOSE
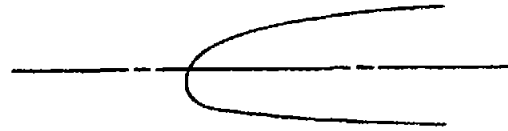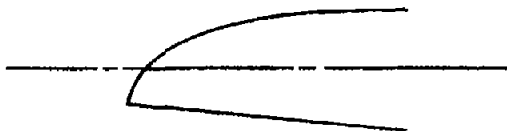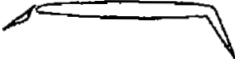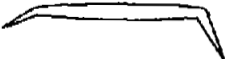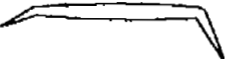
CONFIGURATION 1			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
10.458	-1.133	10.458	-1.133
10.667	-.512	11.250	-1.204
10.833	-.225	12.917	-1.354
11.250	.233	15.000	-1.533
12.083	.808	16.667	-1.667
12.917	1.142	18.333	-1.792
13.750	1.346	20.000	-1.922
15.000	1.533		
16.667	1.667		
18.333	1.792		
20.000	1.922		

CONFIGURATIONS 2 and 3			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
11.000	-.417	11.000	-.417
11.167	.079	11.167	-.917
11.333	.283	11.333	-1.079
11.500	.425	11.500	-1.175
11.667	.550	11.667	-1.233
12.083	.808	11.875	-1.258
12.917	1.142	12.083	-1.283
13.750	1.346	12.917	-1.354
15.000	1.533	15.000	-1.533
16.667	1.667	16.667	-1.667
18.333	1.792	18.333	-1.792
20.000	1.922	20.000	-1.922

L.E. radius: 0.833 $x = 11.833$
$y = -0.417$

TABLE III

SUMMARY OF MAXIMUM-LIFT CHARACTERISTICS FOR LEADING-EDGE SLAT AND DROOPED-NOSE FLAP CONFIGURATIONS FOR THE
NACA 2S-(50)(03)-(50)(03) AIRFOIL

Profile	Config-uration	$c_{l_{max}}$	$\alpha_{c_{l_{max}}}$ (deg)	$\Delta c_{l_{max}}$	$\Delta \alpha_{c_{l_{max}}}$	x_s (percent chord)	y_s (percent chord)	gap (percent chord)	δ_s or δ_N (deg)	δ_F (deg)	R	Figure
		.73	8	—	—	—	—	—	—	—	6x10⁶	4(a) of refer-ence 1
		1.63	2.5	0	0	—	—	—	—	60	6	5(a) of refer-ence 1
	1	2.00	14	.37	11.5	4.23	-.26	1.06	30	60	2	7
	2	1.94	14	.31	11.5	3.81	-.26	.82	30	60	2	7
	3	2.02	16	.39	13.5	4.23	.52	1.73	30	60	2	7
	A	1.95	9	.32	6.5	—	—	—	27	60	2	11
	B	1.96	9	.33	6.5	—	—	—	27	60	2	11

13

CONFIGURATION 1

60°

CONFIGURATION 2

60°

CONFIGURATION 3

60°

27°

CONFIGURATION A

60°

sharp corner

27°

CONFIGURATION B

60°

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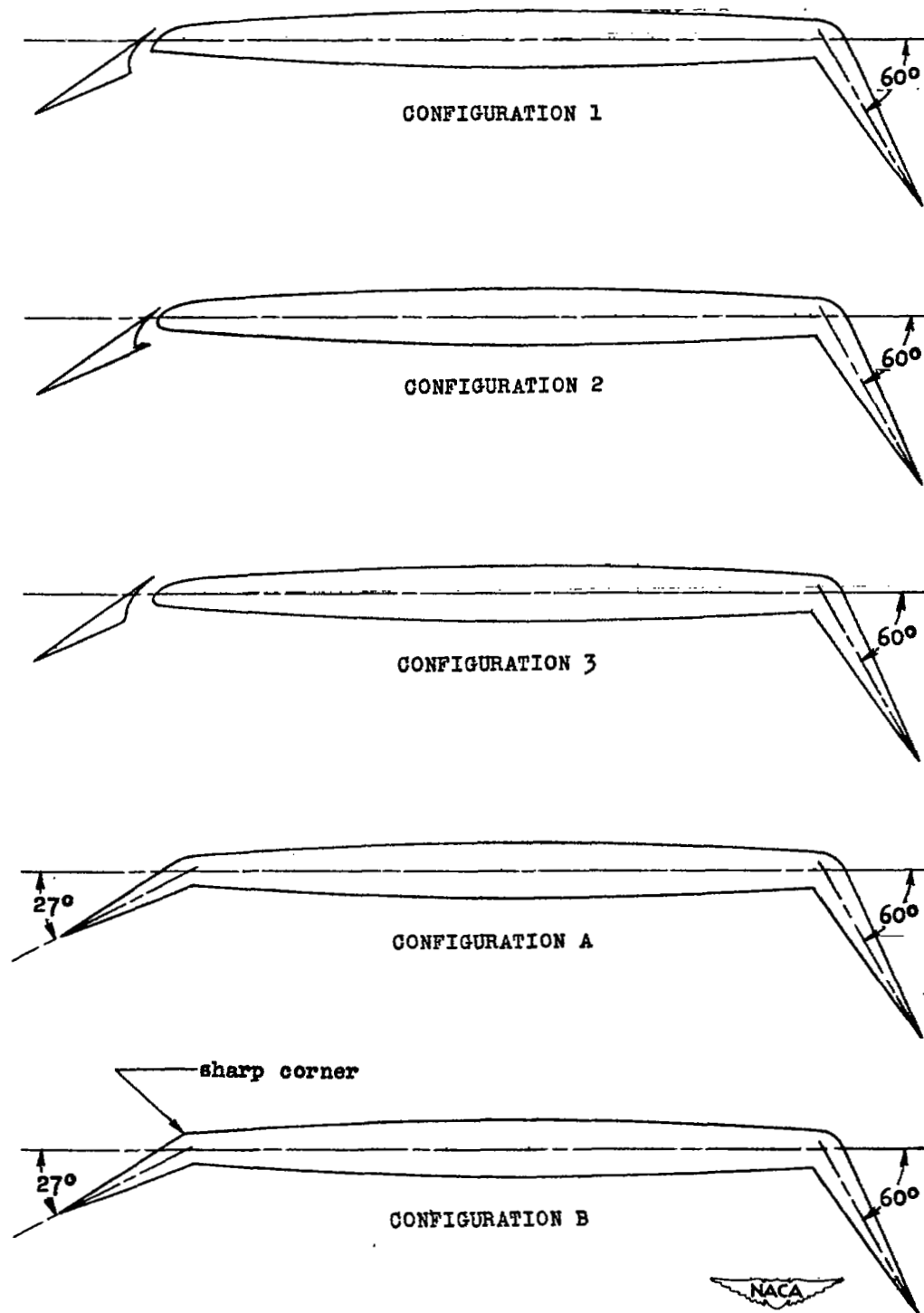
Figure 1.- Symmetrical circular-arc airfoil with leading-edge and
trailing-edge high-lift devices.

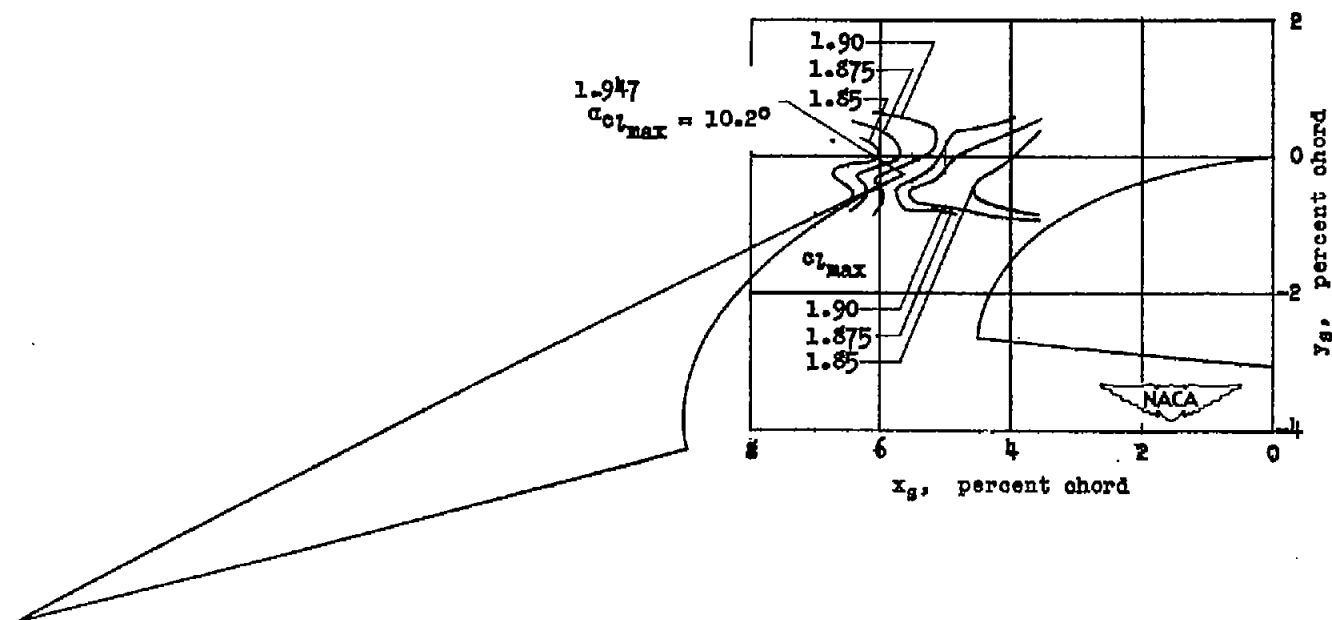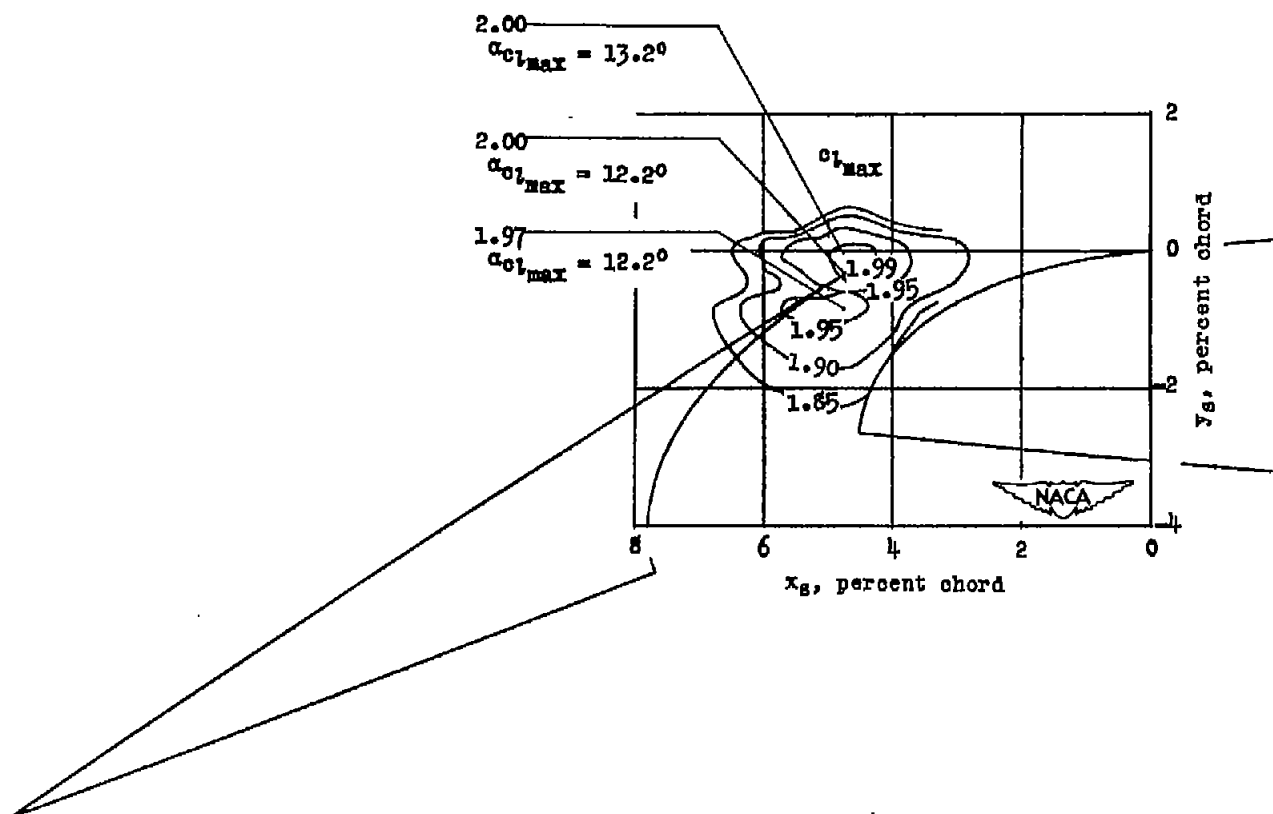Figure 2.- Model end plate used with slat configurations.

Reference point (0.15c)

x_s

y_s

gap

Airfoil chord line

δ_s

Slat chord line

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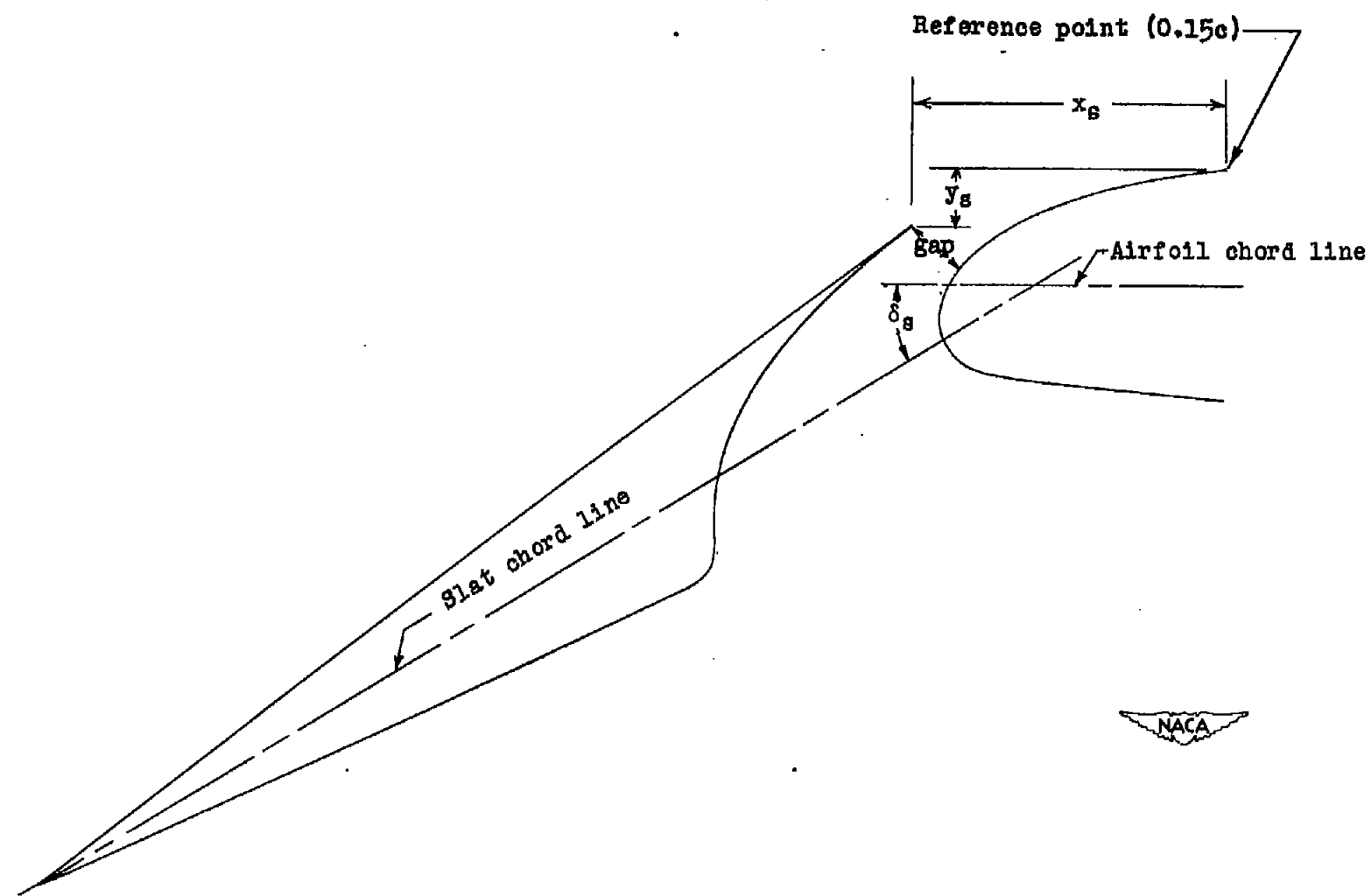
Figure 3.- Variables used to indicate position of leading-edge slat.
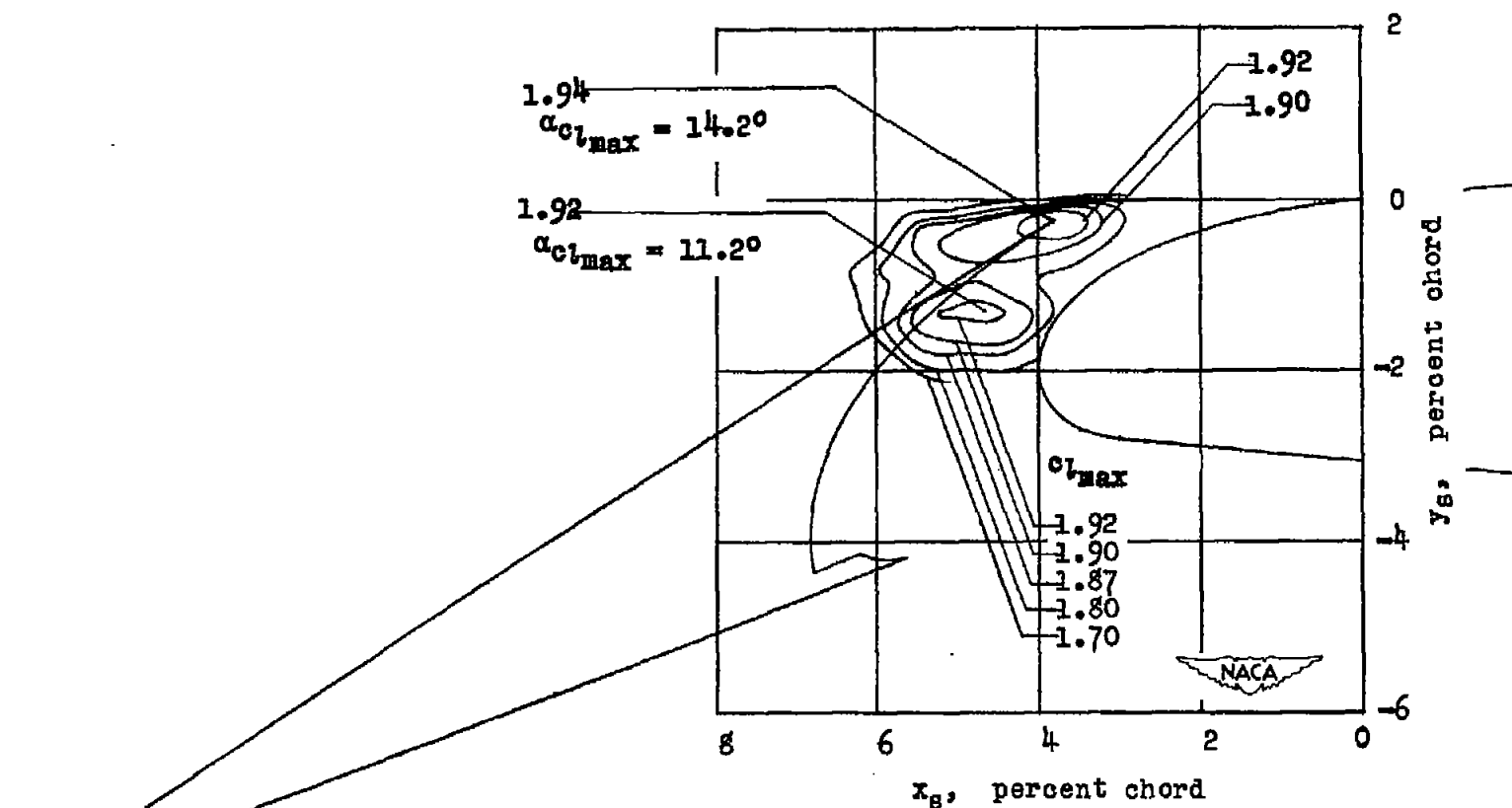
(a) $\delta_s = 19.75^\circ$.

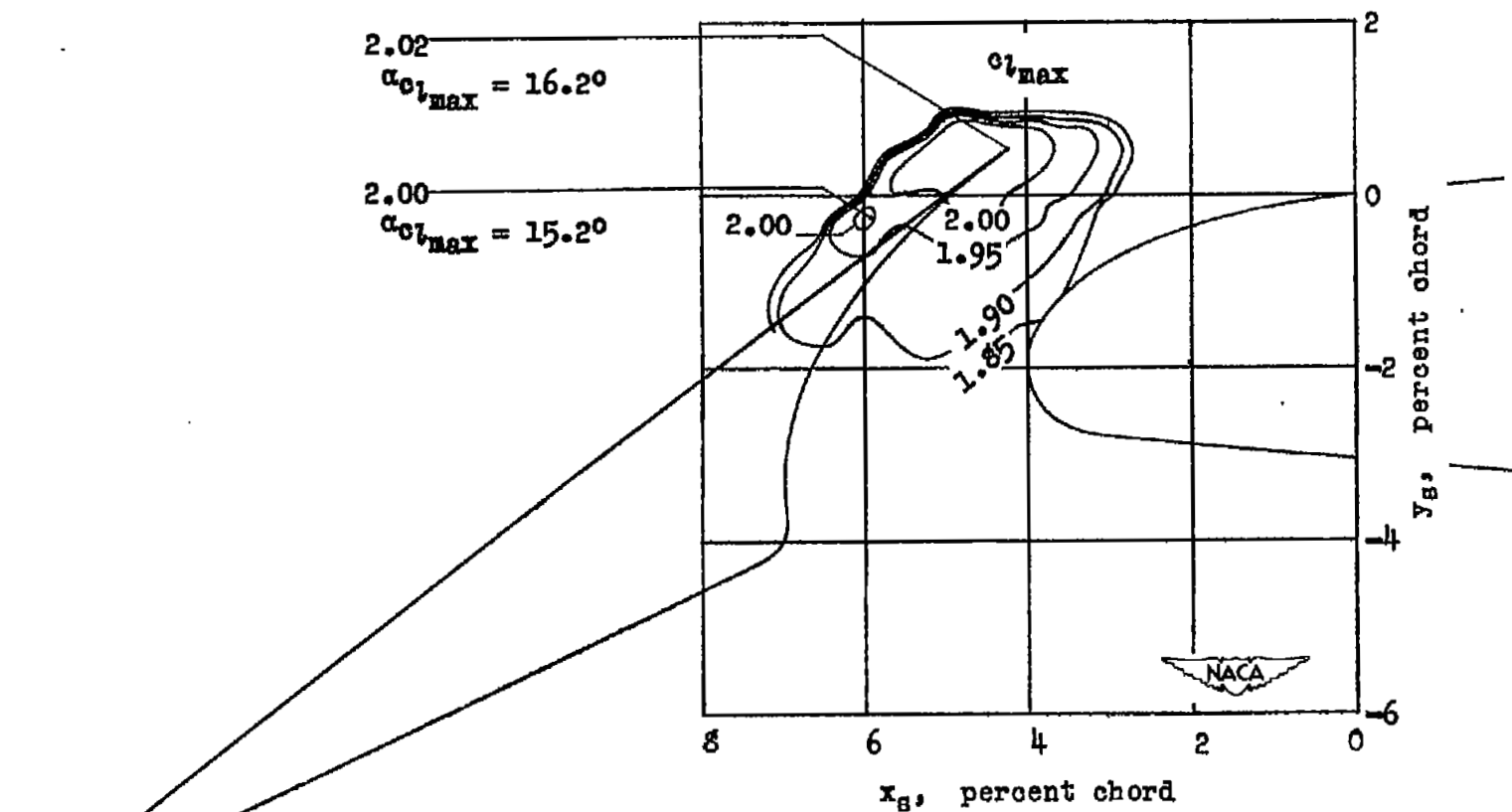Figure 4.- Contours of maximum section lift coefficient for various positions of a 0.15c leading-edge slat on a 6-percent-thick symmetrical circular-arc airfoil. Configuration 1; $R = 2 \times 10^6$.

(b) $\delta_8 = 25.5^\circ$.

Figure 4.- Continued.

2.00

$\alpha_{c_{l_{max}}} = 14.2^{\circ}$

$c_{l_{max}}$ 2.00
1.975
1.95
1.925
1.90
1.875

NACA

y_s, percent chord

2

0

2

4

6   4   2   0

x_s, percent chord

(c) $\delta_s = 30^{\circ}$.

Figure 4.- Continued.

$c_{l_{max}}$

1.70
1.75
1.80
1.825
1.85

1.88
$\alpha_{o_{l_{max}}} = 10.2$

y_s, percent chord

2

0

2

NACA

8   6   4   2   0

x_s, percent chord
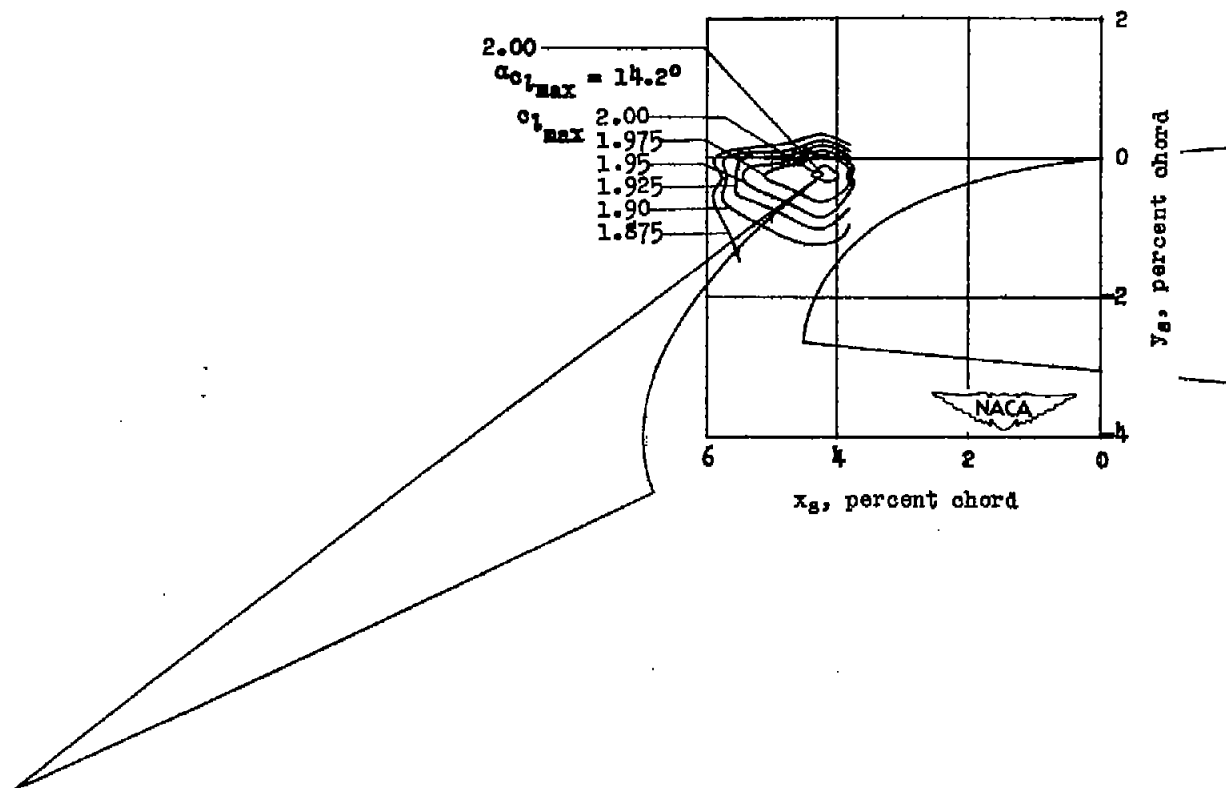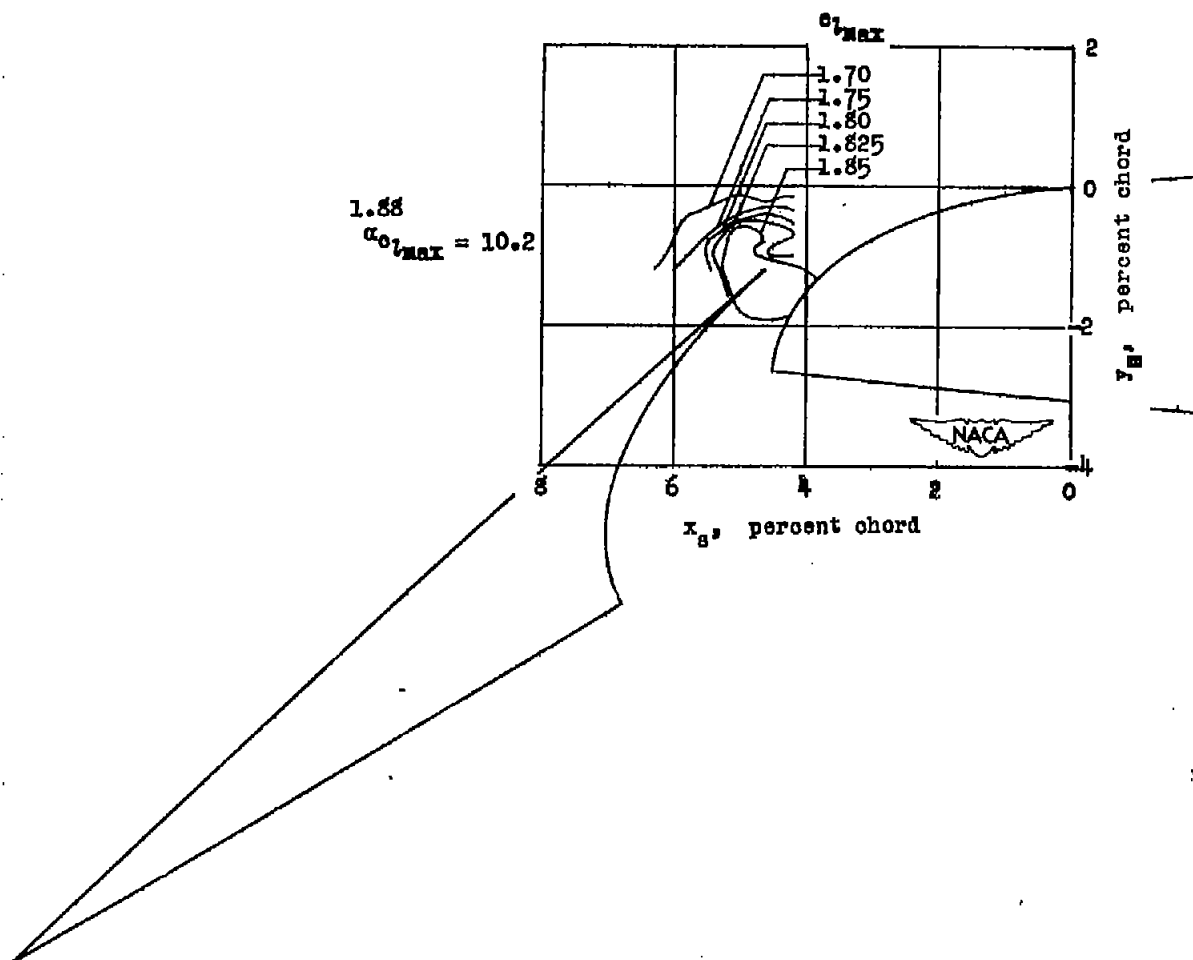
(d) $\delta_s = 35.25^\circ$.

Figure 4.- Concluded.

Figure 5.- Contours of maximum section lift coefficient for various positions of the 0.15c leading-edge slat on a 6-percent-thick symmetrical circular-arc airfoil. Configuration 2; $\delta_s = 30^\circ$; $R = 2 \times 10^6$.
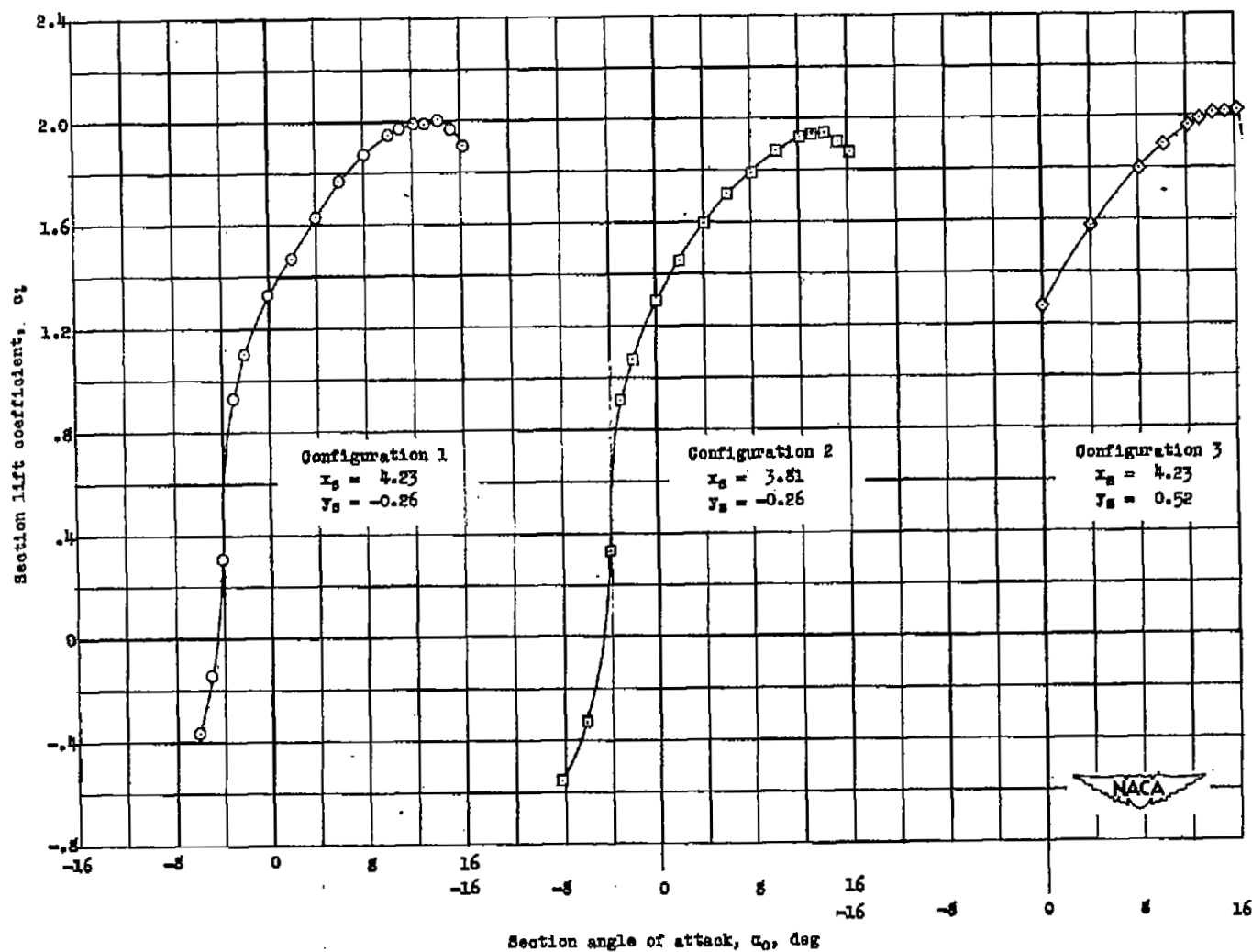
Figure 6.- Contours of maximum section lift coefficient for various positions of the 0.15c leading-edge slat on a 6-percent-thick symmetrical circular-arc airfoil. Configuration 3; $\delta_s = 30^\circ$; $R = 2 \times 10^6$.

Figure 7.- Section lift characteristics of 6-percent-thick symmetrical circular-arc airfoil for various slat configurations. $\delta_s = 30°$; $R = 2 \times 10^6$.
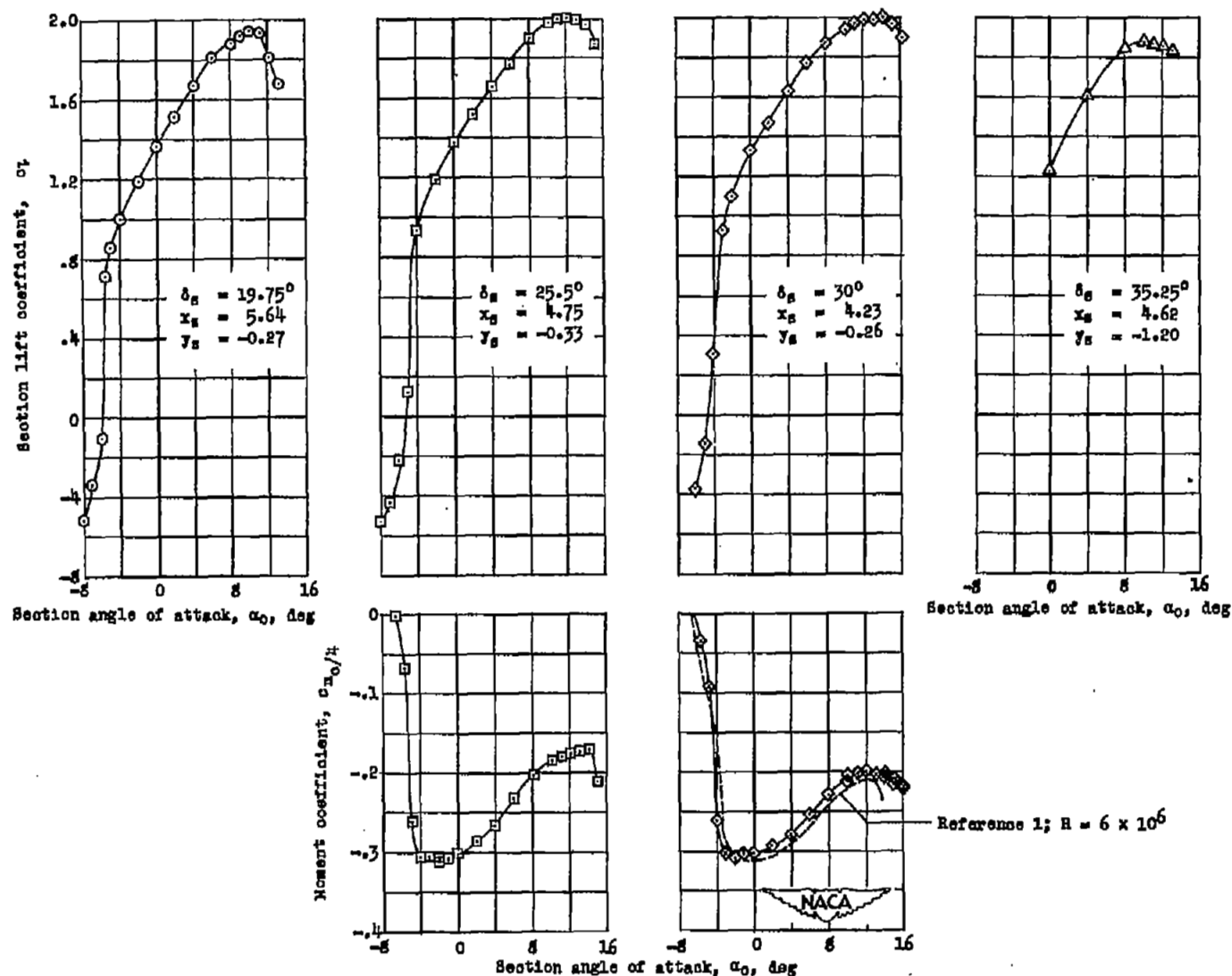
Figure 8.- Section lift and pitching-moment characteristics of 6-percent-thick symmetrical circular-arc airfoil for various deflections of the leading-edge slat. Configuration 1; $R = 2 \times 10^6$.
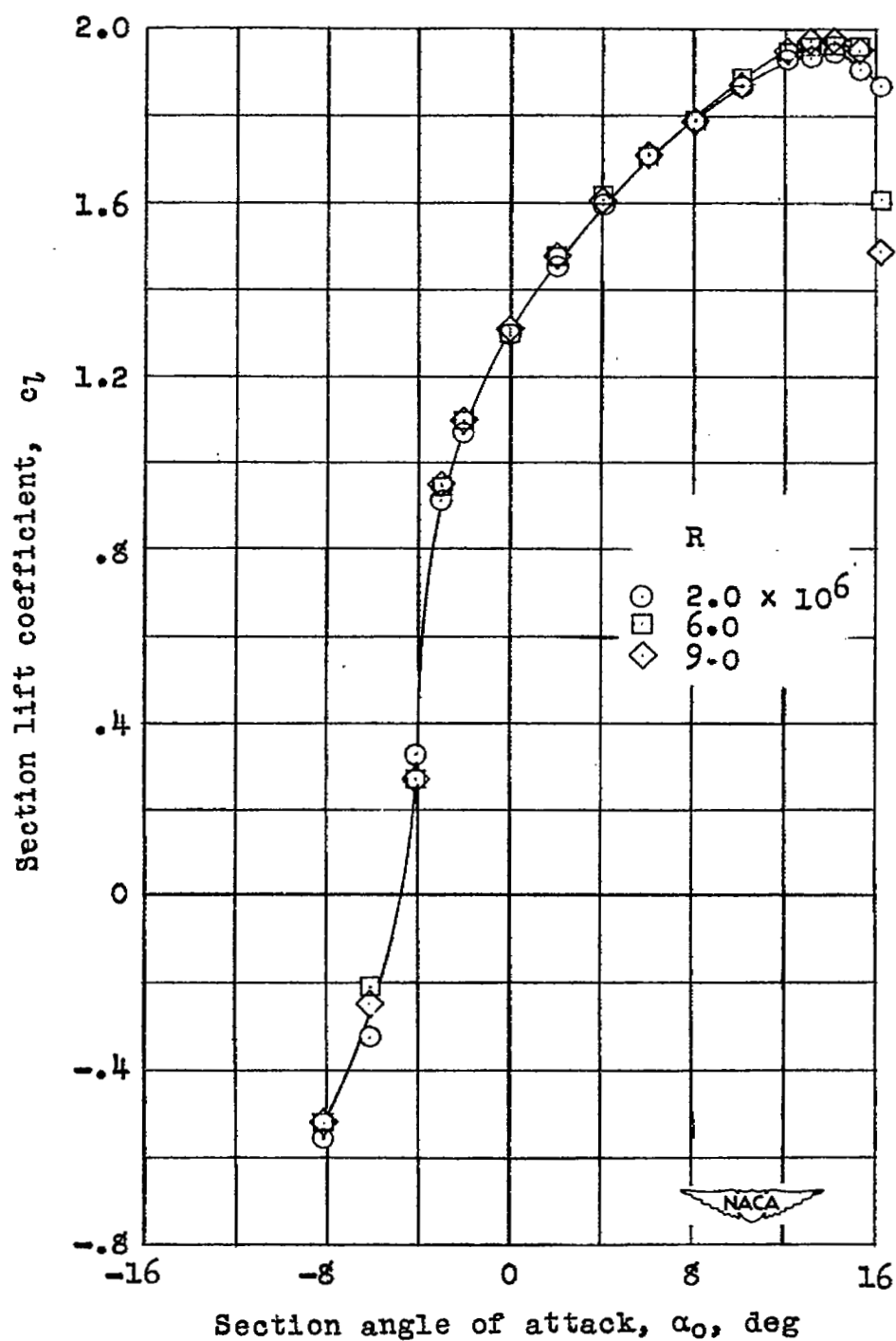
Figure 9.- Section lift characteristics at three values of the Reynolds number for 6-percent-thick symmetrical circular-arc airfoil with leading-edge slat. Configuration 2; $\delta_s = 30°$; $x_s = 3.81$; $y_s = -0.26$.
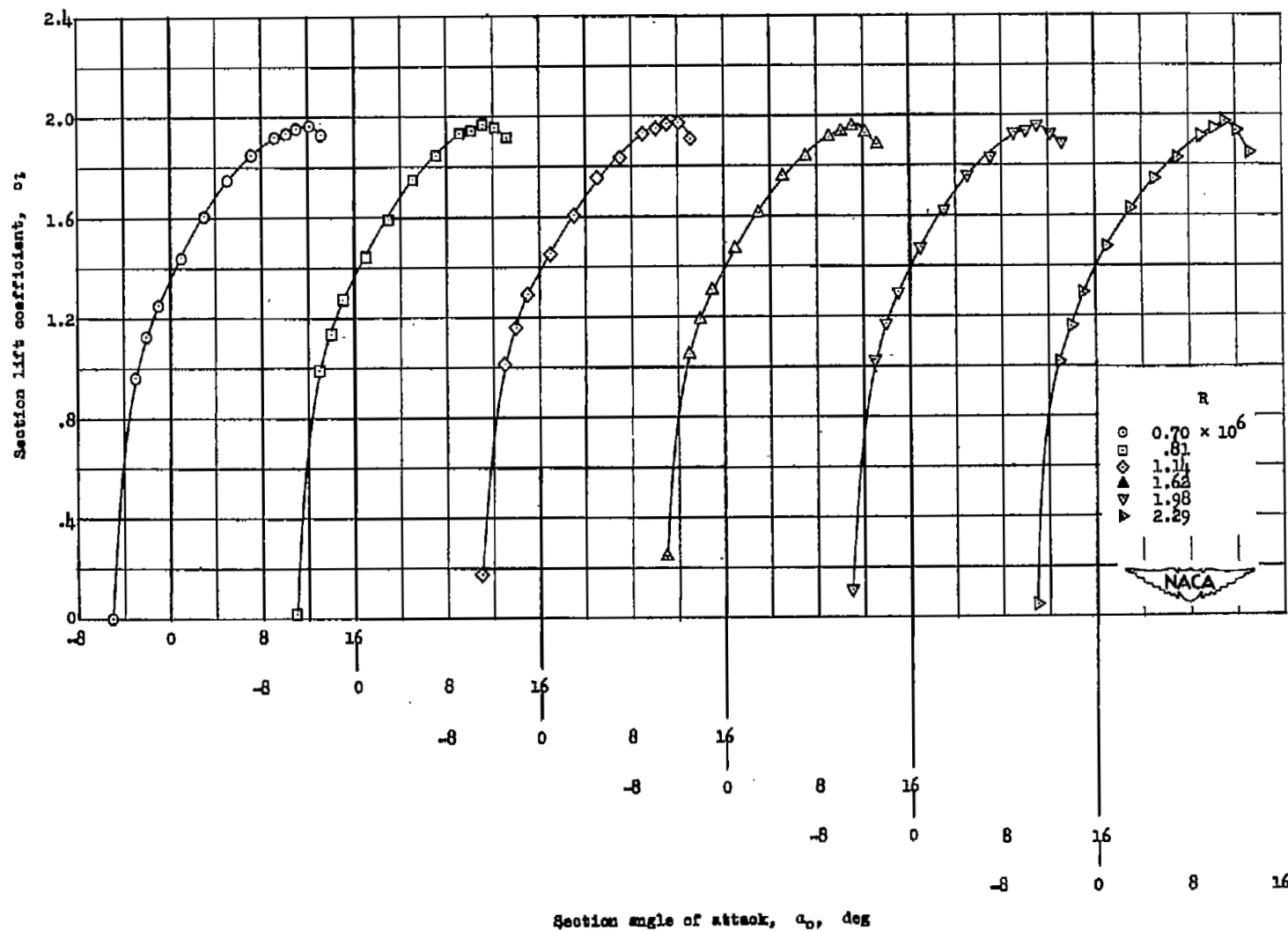
Figure 10.- Section lift characteristics at several values of the Reynolds number for 6-percent-thick symmetrical circular-arc airfoil with drooped-nose flap. Configuration A.
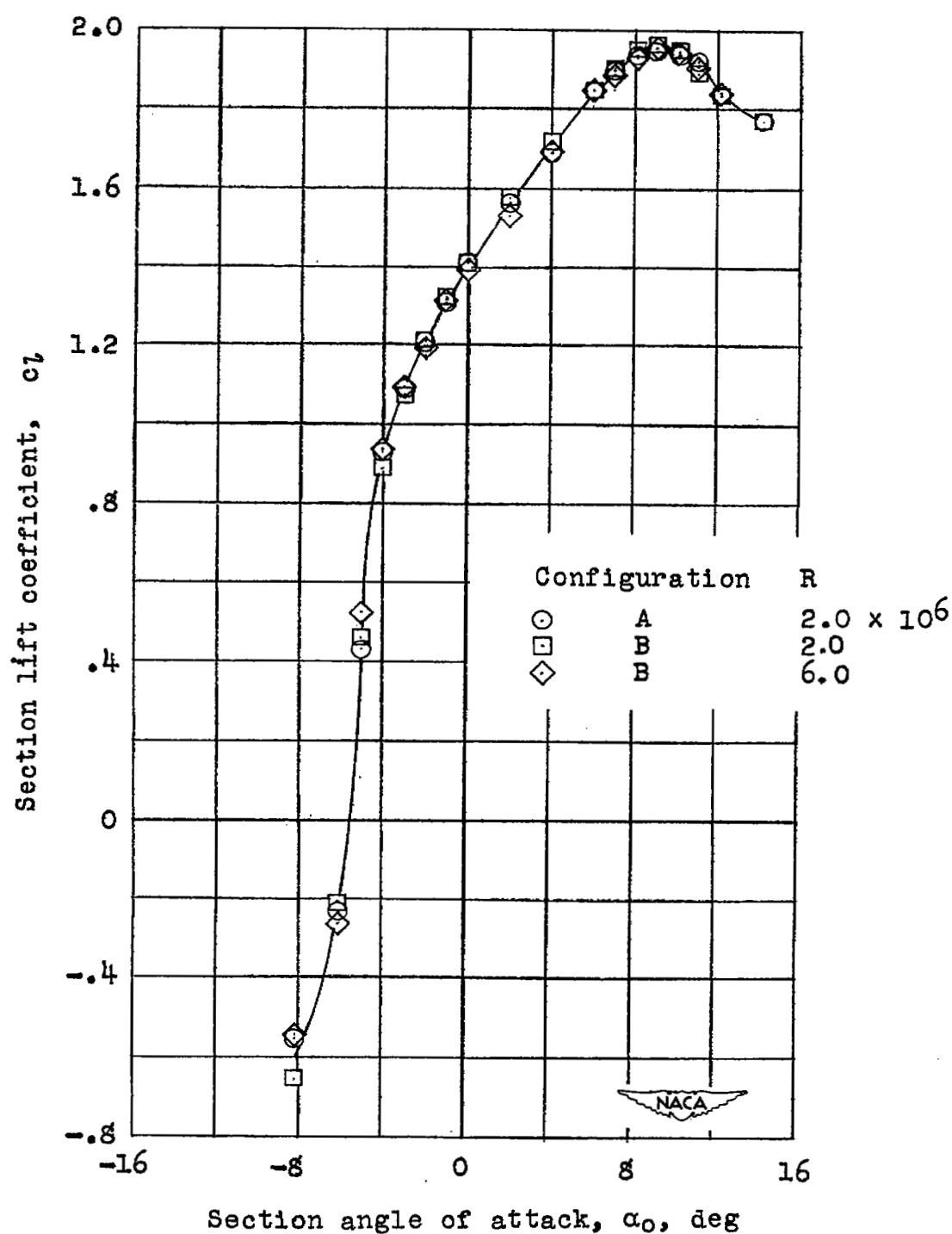
Figure 11.- Section lift characteristics at two values of the Reynolds number for two drooped-nose-flap configurations of 6-percent-thick symmetrical circular-arc airfoil.
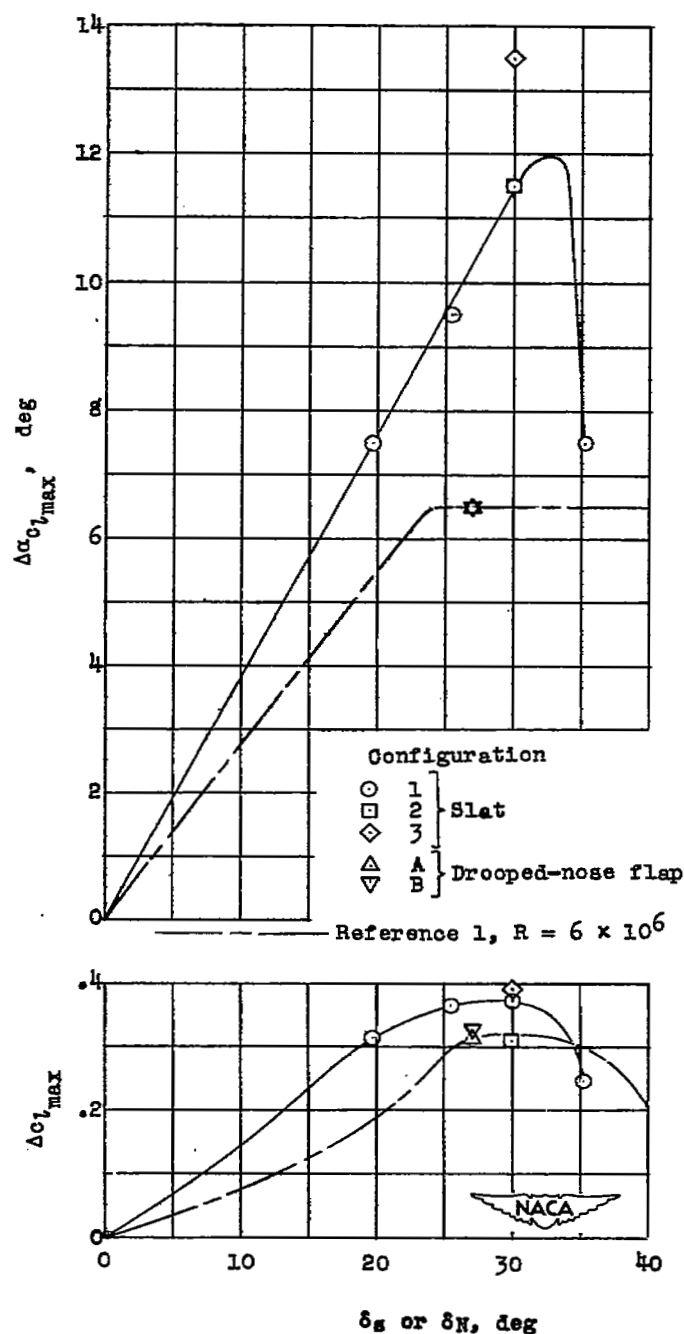
Figure 12.- Variation of the increment in maximum section lift
coefficient and the increment in angle of attack for maximum
section lift coefficient with deflection of the leading-edge
high-lift devices on 6-percent-thick symmetrical circular-arc
airfoil. R = 2 × 10⁶.